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The two protons emitted in the decay of ^{54}Zn have been individually observed for the first time in a Time Projection Chamber. The total decay energy and the half-life measured in this work agree with the results obtained in a previous experiment. Angular and energy correlations between the two protons are determined and compared to theoretical distributions of a three-body model. Within the shell model framework, the relative decay probabilities show a strong contribution of the p^2 configuration for the two-proton emission. After ^{45}Fe, the present result on ^{54}Zn constitutes only the second case of a direct observation of the ground state two-proton decay of a long-lived isotope.

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The study of exotic decays is an efficient tool to explore the structure of nuclei at the proton drip-line. In particular, the emission of two protons from the ground state of a radioactive nucleus has been searched for since 1960, when two-proton (2p) radioactivity was predicted by Goldansky [1] for nuclei beyond the proton drip line, for which one-proton emission is energetically prohibited. This new nuclear decay mode was observed first in the decay of ^{45}Fe in two independent experiments [2, 3] and later also in ^{54}Zn [4] and possibly in ^{48}Ni [5]. In these experiments, the ions of interest were deeply implanted in silicon detectors in which the decay was observed. Therefore, only the total decay energy, the half-life, and the absence of β particles from the competing decay by β-delayed-particle emission could be clearly established. In addition, the observation of the daughter decay helped to unambiguously assign the observed decay to 2p radioactivity. These experimental results were found in reasonable agreement with predictions from different theoretical models [6], like the R-Matrix theory [7], the Shell Model embedded in the Continuum (SMEC) [8] or the three-body model [9, 10].

However, in none of these experiments, the two protons were identified separately, while the main physics question in the context of 2p radioactivity is how the two protons emitted are correlated in energy and in angle. An answer to that would enable us to investigate the decay dynamics of 2p radioactivity and thus reveal details of nuclear structure at the limits of stability. In particular, these studies should reveal the single-particle ordering and other details of the wave function.

In an experiment performed in 2005 at GANIL, emission of two protons in the decay of ^{45}Fe was observed directly for the first time with a Time Projection Chamber (TPC) [11]. The purpose of this detection set-up is to reconstruct the proton tracks in three dimensions. In another experiment performed at MSU [12, 13], the 2p emission in the decay of ^{45}Fe was observed with an Optical Time Projection Chamber in which images of ionizing particle trajectories are recorded optically. In this latter work, high statistics data allowed the authors to obtain a first meaningful comparison with a model including the three-body dynamics of the process [9, 10].

In this Letter, we report on an experiment where emission of two protons in the decay of ^{54}Zn was observed with the TPC. Angular and energy correlations have been determined. These results allowed a first comparison with theoretical predictions of the three-body model and the nuclear shell model.

The ^{54}Zn nuclei were produced by quasi-fragmentation of the projectile at GANIL. A primary ^{58}Ni^{26+} beam with an energy of 74.5 MeV/nucleon and an average intensity of 3.5 μA was fragmented in a ^{nat}Ni target (200 μm). The ^{54}Zn fragments were selected by a magnetic-rigidity, energy-loss, and velocity analysis by means of the LISE3 separator including an achromatic energy degrader (500 μm of beryllium).

Two silicon detectors located at the end of the spectrometer allowed to identify individually the fragments by means of an energy-loss and time-of-flight analysis. The identification parameters were first determined for frequently produced nuclei. Then, the parameters were extrapolated to unambiguously identify the nuclei produced with low probability. Details of this procedure can be found in [14].

The main setting of the spectrometer was optimized for the production and transmission of ^{54}Zn. During a two weeks experiment, 18 ^{54}Zn nuclei have been produced, as expected according to extrapolations of the cross sections of ^{55,56}Zn [15] and ion beam optical calculations. These ions were finally implanted in the TPC [16].

This detector is based on the principle of a time-projection-chamber. Ions of interest are implanted in a gas volume (argon 90% - methane 10%) at 750 mbar, where the radioactive decay takes place. The electrons, produced by the slowing down of either the incoming ions or the decay products, drift in the electric field of the TPC towards a set of four gas electron multipliers (GEM) where they are multiplied and finally detected in a two dimensional strip detector. The analysis of energy signals allows to reconstruct the tracks of the particles in two dimensions; the drift-time analysis gives the third one. Details can be found in [16].

Among the eighteen ^{54}Zn implantation events, only thirteen could be correlated in time and space with decays. Five decay events were lost due to the data acquisition dead time and the short half-life of ^{54}Zn. For two decay events, no information about the energy was obtained because the protons emitted did not stop in the active volume of the chamber. For the first event, the range of the protons emitted was very long (more than 8 cm). Such a long range is only compatible with a beta-delayed proton emission. For the second event, due to the large momentum acceptance of the LISE3 spectrometer and the large range distribution of ^{54}Zn, the ion was implanted at the entrance of the TPC. The protons were emitted backwards and left the active volume. The other eleven decay signals could be analyzed in detail except one, for which a spurious response of one set of strips did not allow us to extract the relevant information. From this information, the branching ratio for 2p emission is determined as BR = 92^{+6}_{-13}%.

The time difference between an implantation event and its subsequent decay event allowed a determination of the half-life of ^{54}Zn. This spectrum is shown in the left part of Figure 1. The half-life is determined as $1.59^{+0.60}_{-0.35}$ ms. Measurements of charge signals from the GEMs give access to the total decay energy. The right part of Figure 1 shows the signal extracted from the third GEM, the decay energy being thus determined to 1.28±0.21 MeV. As can be seen from Table I, all these decay observables are in agreement with those determined in [4]. If we combine the present experimental BR and half-life with the previous values, we obtain BR = 90^{+5}_{-10}% and $T_{1/2}$ = $1.78^{+0.66}_{-0.76}$ ms, leading to a 2p partial half-life of $T^{2p}_{1/2}$ = $1.98^{+0.73}_{-0.41}$ ms.

Observables related to the measurements of individual protons were also determined. As an example, an implantation event spectrum is presented in Figure 2. The

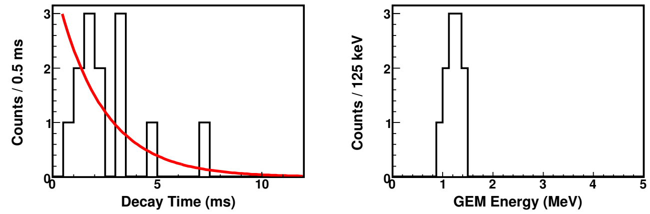

FIG. 1: Left: Decay-time distribution obtained in the decay of ^{54}Zn, giving rise to a half-life of $1.59^{+0.60}_{-0.35}$ ms. Right: Energy spectrum of the ^{54}Zn decay events determined with the charge signals of one GEM. The total decay energy E_{2p} = 1.28±0.21MeV is estimated from eleven events in the peak (see text for more details).

Experiments	$T_{1/2}$ (ms)	Q_{2p} (MeV)	BR (%)
Blank et al.[4]	$3.2^{+1.8}_{-0.8}$	1.48±0.02	87^{+10}_{-17}
this work	$1.59^{+0.60}_{-0.35}$	1.28±0.21	92^{+6}_{-13}

TABLE I: Comparison of the experimental decay observables with the values obtained in a previous experiment.

ion enters with an angle of 45^o in the chamber and stops at a given (X_0,Y_0) position. The implantation signals are fitted with a Gaussian folded with a straight line. This function is a good approximation of the Bragg peak corresponding to the energy loss of the charged particles inside the gas chamber. It allowed to determine the implantation position of the ion (top part), which coincides with the emission position of the two protons (middle part). Their tracks in X and Y are fitted with the same function as for the implantation signals: the sum of two foldings of a straight line and a Gaussian, with the main constraint that the energy of a proton is the same along the X and Y direction. Figure 3a shows an example of a two-proton emission in two dimensions.

The energy fraction distribution of the individual protons as determined from the energy signals is plotted in Figure 4 and is found in good agreement with the predictions of the three body model. As expected in a simultaneous emission, the two protons share the decay energy equally in order to favor the barrier penetration. This theoretical approach [9, 10] is the only model of 2p radioactivity which takes into account correlations between the two protons.

In a final step, the third component Z of the tracks was obtained. The bottom of Figure 2 shows the time spectra corresponding to the same event. Only the spectrum on the Y dimension is analyzed because the protons were emitted along the X strips. The spectrum is fitted by a straight line for each proton, giving the third component of each proton track. This drift-time analysis will be described in detail in a subsequent paper. Briefly, due to the short range of the protons, the determination of

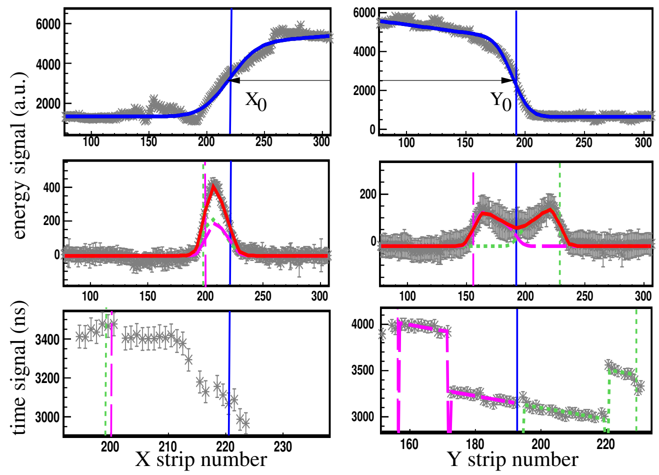

FIG. 2: Example of energy loss spectra obtained with the XY strip detector and associated with the implantation of a 2p-emitter in the TPC. Top: Signals obtained for the implantation of ^{54}Zn: the ion enters in the chamber and stops at a given (X_0,Y_0) depth. The arrows indicate the direction of the incoming beam. The solid line is the fit of the implantation profile whereas the vertical line indicates the determined implantation position. Middle: The decay of ^{54}Zn takes place at the stopping point of the implantation event described above. The two protons are clearly identified. Their tracks are determined by fitting the decay signal with a sum of two foldings of a straight line and a Gaussian. The vertical full line corresponds to the starting point of the trajectories determined from the implantation profile of ^{54}Zn whereas the dashed lines are the two stopping points of the protons trajectories. Bottom: Corresponding time signals. The spectrum on the Y dimension is fitted by a straight line for each proton track, giving the directions of each individual proton.

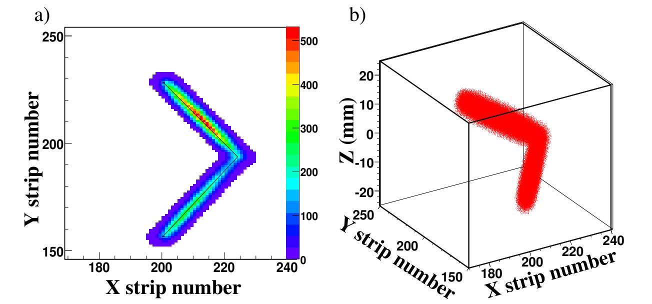

FIG. 3: a) Two-dimensional view of a ^{54}Zn decay event as reconstructed from the XY strip detector. The color corresponds to the energy loss detected by the strips. b) Same decay event reconstructed in the three-dimensional space.

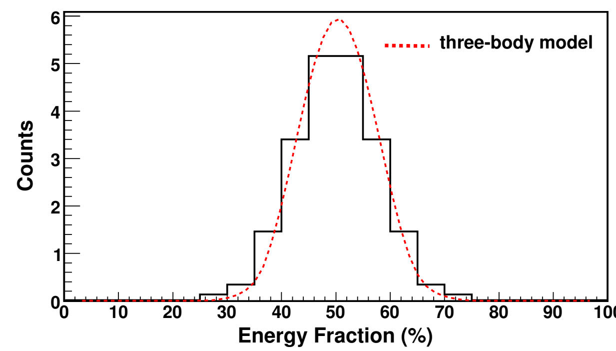

FIG. 4: Energy sharing between the two protons emitted in the decay of ^{54}Zn. The dashed line is the energy distribution of the three-body model [10] folded with the response of the detector, which fits well the experimental distribution.

Δz with the time signals is not very accurate. Therefore, the time signals were only used to determine whether the proton goes upwards or downwards. Then, we use the theoretical range r of the protons [17] to determine Δz with $\Delta z^2 = r^2 - \Delta x^2 - \Delta y^2$, with Δx and Δy given by the energy signal analysis. The theoretical range was calculated by taking the energy sharing of the protons, as determined from the energy spectra analysis, and the sum energy, as determined from the previous measurements [4].

Among the ten events, seven have been fully reconstructed in the three dimensional space. For the three remaining, the time signals did not allow to determine if the protons went up or down. Therefore, we have for these events two possible angles between the two protons: the first one if the protons are emitted in the same hemisphere (up or down), the second one if they are emitted in different hemispheres. Figure 3b shows an example of a two-proton emission reconstructed in three dimensions.

The complete analysis of these decay events allowed to provide angular correlations between the protons. The upper part of Figure 5 shows each experimental angle, represented by a Gaussian reflecting the angular resolution. The middle part shows the angular distribution obtained. Seven events are represented in the histogram; the three other events, not fully reconstructed, are represented by full lines for the first possibility and by dashed lines for the second. In all cases, these three events are located below 90^o. Within the three body model, the angular distribution spectra are calculated for different ℓ^2 configurations of the two emitted protons. The corresponding spectra (bottom part of Figure 5) show a double-hump structure, with one broad peak centered around 50^o and a smaller one at about 145^o. When the p^2 contribution becomes negligible, the second hump does not survive. Considering that the experimental distribution shows a double-hump structure, the results can be compared with the model predictions by looking at the ratio between the first and the second hump. From an interpolation of the theoretical ratios, we obtain an experimental p^2 contribution of 30^{+33}_{-21}%. This number can be compared to a shell model wave function decompo-

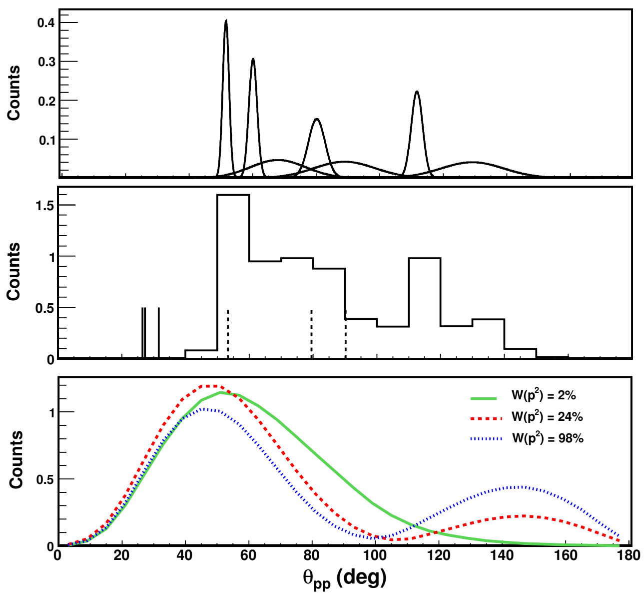

FIG. 5: Top: Experimental angles between the two protons in the three dimensional space. Each event is convoluted with a Gaussian representing the angular resolution. Middle: Experimental angular distribution between the two protons. Seven events are represented in the histogram. The dashed and full lines represent two possible angles for three not fully reconstructed events. Bottom: The three lines are the theoretical predictions of the three-body model, each line corresponding to different weights of the p^2 configuration. These model distributions are folded with a Gaussian function representing the detector angular resolution.

sition over the same p^2 and f^2 contributions using the GPFX1A Hamiltonian [18] which yields about 80% for the p^2 contribution.

In the following, we will combine the shell model and the three-body model to determine theoretical half-lives. While the three-body model is adapted to treat the dynamics of the 2p emission, the shell model is more appropriate to describe the nuclear structure. Therefore, we use the spectroscopic factors of the shell model and the partial half-lives from the three-body model to determine the relative decay probabilities of the two ℓ^2 configurations, and thus to compare the experimental and the theoretical half-life. Two-proton removal amplitudes of a pair of protons have been calculated using the GPFX1A Hamiltonian [18] and are found to be 0.3159, 0.3121, 0.6539, 0.2631 for the $(0f_{7/2})^2$, $(0f_{5/2})^2$, $(1p_{3/2})^2$ and $(1p_{1/2})^2$ configurations, respectively. In LS coupling, the S=L=0 removal amplitudes are 0.443 and 0.686 for $(0f)^2$ and $(1p)^2$ configurations, respectively. Combining the half-lives calculated by the three-body model for pure configurations (45 ms and 0.91 ms for $(0f)^2$ and $(1p)^2$, respectively) with the shell model removal amplitudes, we obtain the "shell model corrected" partial half-lives $T_{1/2}(0f^2) = 45/0.443^2 = 230$ ms and $T_{1/2}(1p^2) = 0.91/0.686^2 = 1.9$ ms. The total half-life of the 2p emission is therefore calculated by adding the two partial decay amplitudes coherently, with $\sqrt{1/T_{1/2}^{2p}} = \sqrt{1/1.9}+\sqrt{1/230}$, giving $T_{1/2}^{2p} = 1.6$ ms. This value is in excellent agreement with the experimental value obtained in this work ($T_{1/2}^{2p} = 1.98^{+0.73}_{-0.41}$ ms). From the above values, we can now derive the relative decay probability through the $(0p)^2$ configuration which is $P(p^2) = (1/1.9)/((1/1.9)+(1/230)) = 0.99$. This means that almost all the decay strength goes through the $(0p)^2$ configuration of the wave function. An analysis of the experimental data from ^{45}Fe and ^{54}Zn in the frame work of the models used here will be the subject of a future publication [19].

In summary, we observed directly for the first time the two protons emitted in the decay of ^{54}Zn with a TPC. Half-life and Q-value were determined and were found in good agreement with previous experiments and theoretical models. Energy and angular distributions could be obtained and allowed a first rough comparison with theoretical models giving information about nuclear structure. However, to establish a detailed picture of the decay process, higher statistics of implantation-decay events are needed, which can be obtained in a future experiment. In parallel, improvements of theoretical model predictions are essential to elucidate the decay mechanism which governs two-proton radioactivity.

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